Low-frequency noise in amorphous indium-gallium-zinc oxide thin-film transistors from subthreshold to saturation

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We investigate the low-frequency noise (LFN) behaviors of amorphous indium-gallium-zinc oxide thin-film transistors in the subthreshold, Ohmic, and saturation regimes. Measured LFNs are proportional to $1/f^\gamma$, with $\gamma=0.8–0.9$ in all operation regimes. It is found that the LFN behavior follows the carrier number fluctuation model in the subthreshold regime, whereas in the Ohmic and saturation regimes, it agrees well with the bulk mobility fluctuation model. We also observe that the origin of $1/f$ noise in the Ohmic regime changes from the bulk mobility fluctuation to the carrier number fluctuation as the channel length decreases. © 2010 American Institute of Physics. [doi:10.1063/1.3491553]

Since the first demonstration of thin-film transistors (TFTs) using amorphous indium-gallium-zinc oxide (a-IGZO) for their channel material,1 a-IGZO TFTs have been under active research and development due to their high mobility and good transparency, as well as a low-temperature process that allows the fabrication of TFTs and circuits on flexible substrates.2,3 Recently, much effort has been made to implement high-performance circuits based on the a-IGZO TFTs.4–6 However, very limited knowledge is still available for the low-frequency noise (LFN) behaviors for a-IGZO TFTs,7,8 although it limits the performance of analog circuits and degrades the noise margins in digital circuits. In our previous work, we report that the LFN of the a-IGZO TFT is mainly due to the bulk mobility fluctuation in the Ohmic regime.7 However, considering that the TFTs can be in the subthreshold or saturation regime during the circuit operation, the LFN in the subthreshold or saturation regime also need to be addressed. In this paper, we investigate and compare the LFN characteristics of a-IGZO TFTs in subthreshold, Ohmic, and saturation regimes. The channel length dependence of the LFN generation mechanism is also investigated for a-IGZO TFTs.

Figure 1(a) shows the schematic cross-section of fabricated a-IGZO TFTs with a staggered bottom gate structure. On a thermally grown SiO$_2$/Si substrate, molybdenum (Mo) as a gate metal was deposited and patterned by a conventional photolithography process. Then, 120 nm thick SiO$_2$ was deposited by plasma-enhanced chemical vapor deposition (PECVD) at 300 °C. The a-IGZO active layer was deposited by rf (13.56-MHz) magnetron sputtering using an IGZO target (Ga$_2$O$_3$:In$_2$O$_3$:ZnO=2:2:1 at. %). The sputtering process was carried out at room temperature (RT) in a mixed Ar/O$_2$ [100:1 at SCCM (SCCM denotes cubic centimeter per minute at STP)] atmosphere. The thickness of the a-IGZO active layer was 50 nm. For the source/drain (S/D) pattern, Mo was sputtered at RT and then patterned by dryetching. After N$_2$O plasma treatment on the channel surface of the IGZO active layer, a SiO$_2$ passivation layer was continuously deposited at 150 °C by PECVD without a vacuum break, and finally, all the samples were annealed at 250 °C for 1 h in the furnace.

Figure 1(b) shows the transfer curves of the a-IGZO TFTs measured at drain-to-source voltages ($V_{\text{DS}}$) of 0.5 and 15 V. The electrical characteristics of the devices were measured with an Agilent 4156 C precision semiconductor parameter analyzer. The curves show the n-type characteristics with a subthreshold slope ($S$) of 0.42 V/decade, a field effect mobility ($\mu_{\text{FE}}$) of 17.4 cm$^2$/V s, a threshold voltage ($V_{\text{TH}}$) of 1.3 V, and an on/off ratio of $\sim10^9$ at $V_{\text{DS}}=15$ V, where $V_{\text{TH}}$ was calculated by fitting a straight line to the plot of the square root of drain-to-source current ($I_{\text{DS}}$) versus gate-to-source voltage ($V_{\text{GS}}$) in the saturation regime. These electrical parameters are comparable to those of the a-IGZO TFTs in recently published literature works,9,10 and hence render it useful for the study of the LFN characteristics of a-IGZO TFTs.

![Schematic cross-section of the fabricated bottom gate a-IGZO TFT.](image)

**FIG. 1.** (Color online) (a) Schematic cross-section of the fabricated bottom gate a-IGZO TFT. (b) Representative transfer curves of the a-IGZO TFT measured at drain-to-source voltages ($V_{\text{DS}}$) of 0.5 and 15 V. The channel width ($W$) and length ($L$) were 40 $\mu$m and 20 $\mu$m, respectively.
FIG. 2. (Color online) Normalized noise power spectral densities \( S_I/I_{DS}^2 \) of the device measured in the subthreshold, Ohmic, and saturation regimes.

Figure 2 shows the normalized noise power spectral densities \( S_I/I_{DS}^2 \) of the device measured in the subthreshold, Ohmic, and saturation regimes using SR570 low-noise current amplifier and Agilent 35670A dynamic signal analyzer. Measurements were made on transistors with a channel width \( (W) \) of 40 \( \mu \)m and a length \( (L) \) of 20 \( \mu \)m at \( V_{DS} = 0.5 \) V and \( V_{GS} = -0.5 \) V (subthreshold regime), \( V_{DS} = 0.5 \) V and \( V_{GS} = 2 \) V (Ohmic regime), and \( V_{DS} = 15 \) V and \( V_{GS} = 2 \) V (saturation regime), respectively. \( S_I/I_{DS}^2 \)s are close to \( 1/f^\gamma \), with \( \gamma = 0.8 \)–0.9 in all operation regimes, which suggests that the \( 1/f \) noise is dominant at low frequencies \((f < 1 \) kHz\) in all regimes for a-IGZO TFTs. The large \( \gamma \) at \( f > 500 \) Hz in the subthreshold regime is because of the limited gain-band width product of the current amplifier used for the noise measurements.

Figure 3(a) depicts \( S_I \) versus \( I_{DS} \) at two drain-to-source voltages \((V_{DS} = 0.5 \) and \( 15 \) V\) measured at a fixed frequency of 10 Hz. At \( V_{DS} = 0.5 \) V, when \( I_{DS} \) increases, we obtain the subthreshold regime followed by the Ohmic one. Figure 3(a) shows that the \( S_I \) follows nearly quadratic variations versus \( I_{DS} \) in the subthreshold regime, which represents that the LFN is mainly due to the carrier number fluctuation, and the charge trapping/detrapping is the origin of LFN in the subthreshold regime for a-IGZO TFTs.\(^{11}\) According to the carrier number fluctuation model,\(^{11}\) the \( S_I \) in the subthreshold regime can be expressed as

\[
S_I = \frac{q^4 N_T}{kTWL} f^{\gamma_{\text{eff}}} \eta^2 I_{DS}^2,
\]

where \( q \) is the elementary charge, \( k \) is the Boltzmann constant, \( T \) is the temperature, \( N_T \) is the density per unit energy of the dielectric trap in the vicinity of the Fermi level, \( \gamma \) is the tunneling parameter of the traps and \( \lambda = 1/\gamma \) is the tunneling attenuation distance \((\sim 0.1 \) nm in SiO\(_2\)), \( C_i \) is the dielectric capacitance per unit area, and \( \eta \) is the parameter which can be obtained from \( S:S = (\ln 10) \eta (kT/q) \). From Eq. (1) and measured results in Figs. 1(b) and 3(a), \( N_T \) is estimated as \(-1.1 \times 10^{19} \) eV\(^{-1}\) cm\(^{-3}\), which is around one or two orders of magnitude higher than the thermal oxide trap densities reported in previous works for silicon transistors.\(^{12}\)

In the Ohmic regime, the \( S_I \) has a linear relationship with \( I_{DS} \), which represents that the LFN is mainly due to the bulk mobility fluctuation, and the electron-phonon scattering is the main origin of LFN in the Ohmic regime.\(^ {13,15} \) From Hooge’s empirical law,\(^ {15} \) the \( S_I \) in the Ohmic regime can be expressed as

\[
S_I = \frac{q \mu_{\text{eff}} \alpha_H}{L^2} \frac{\eta^2 I_{DS}}{f}
\]

where \( \alpha_H \) is the Hooge’s parameter that allows one to compare the noise level in different devices and materials. From Eq. (2) and measured results in Fig. 3(a), \( \alpha_H \) is extracted as \(-6.5 \times 10^{-3}\), which is around two or three orders of magnitude lower than that of the a-IGZO TFTs with Al\(_2\)O\(_3\) gate dielectric in our previous work,\(^ {7} \) and is comparable with that of the amorphous silicon (a-Si) TFTs.\(^ {16,17} \) The comparison of \( \alpha_H \) with a-IGZO TFTs with Al\(_2\)O\(_3\) gate dielectric shows that the magnitude of LFN strongly depends on the gate dielectric in a-IGZO TFTs. In the saturation regime with \( V_{DS} = 15 \) V, the \( S_I \) almost follows the relationship of \( S_I \propto I_{DS}^2 \), which suggests that the generation mechanism of the LFN in the saturation regime is also the bulk mobility fluctuation in a-IGZO TFTs following the equation from Hooge’s empirical law.\(^ {15} \)

\[
S_I = \frac{\alpha_H}{f} q \sqrt{\frac{2}{C_i}} \mu_{\text{eff}}^{1/2} \frac{I_{DS}^{3/2}}{L^{3/2}}
\]

Another method of finding the dominant mechanism of \( 1/f \) noise is to investigate the dependence of \( S_I/I_{DS}^2 \) on the gate overdrive voltage \((V_{GS-V_{TH}})\) at a fixed frequency.\(^ {18} \) Figure 3(b) shows that the \( S_I/I_{DS}^2 \) varies as \((V_{GS-V_{TH}})^2\) at a fixed frequency of 10 Hz in both of Ohmic and saturation regimes and the \( S_I/I_{DS}^2 \) measured in the saturation regime is about two times higher than that in the Ohmic regime. These results are in good agreement with the prediction of Hooge’s empirical law, and confirm our previous conclusion that the dominant LFN generation mechanism is the bulk mobility fluctuation in the Ohmic and saturation regimes. The constant slope in Fig. 3(b) also suggests that the S/D contact noise can be negligible, and the LFN mainly comes from the intrinsic channel region in fabricated devices.\(^ {19} \)

Figure 4(a) depicts the dependence of \( S_I/I_{DS}^2 \) on \( V_{GS-V_{TH}} \) in TFTs with different channel lengths \((L = 4, 10, 20 \mu \text{m})\). Measurements were made at a fixed frequency of 10 Hz in the Ohmic regime for all devices. The results show that the slope progressively changes from \((-1)\) to \((-2)\) as the channel length decreases, which represents the dominant LFN generation mechanism in the Ohmic regime changes...
from the bulk mobility fluctuation to the carrier number fluctuation with the reduction in channel lengths in a-IGZO TFTs. To investigate whether this phenomenon is caused from different interface trap densities, we compared the transfer curves of devices with different channel lengths. Figure 4(b) shows that the $S$ values of the transfer curves obtained from TFTs with different channel lengths ($L=4$ and $20 \ \mu m$) are very similar, which suggests that the modification of the LFN generation mechanism is not because of the degraded interface during the fabrication process in short channel devices. Although the actual physical mechanism is not clearly known yet, this behavior was also reported in p-channel metal-oxide-semiconductor field-effect transistors and a-Si TFTs. The observed results show that the interface quality improvement becomes more important for the LFN reduction in short channel a-IGZO TFTs.

In this paper, the LFN behaviors are investigated for a-IGZO TFTs in the subthreshold, Ohmic, and saturation regimes. Measured LFNs fit well to $1/f$ power law, with $\gamma=0.8-0.9$ in all operation regimes, which suggests that the $1/f$ noise is dominant at low frequencies in all regimes. We find that the $1/f$ noise can be interpreted in terms of the carrier number fluctuation model in the subthreshold regime, however agrees well with the prediction of the Hooge’s bulk mobility fluctuation model in the Ohmic and saturation regimes. $\alpha_H$ is extracted as $\sim 6.5 \times 10^{-3}$ in the Ohmic and saturation regimes, which is comparable with that of the a-Si TFTs. We also observe that the LFN generation mechanism in the Ohmic regime changes from the bulk mobility fluctuation to the carrier number fluctuation with the reduction in channel lengths, which suggest that the noise by the charge trapping/detraping at the interface becomes more dominant in short channel a-IGZO TFTs.

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